CoAction Publishing

Climate impacts on environmental risks evaluated from space: a conceptual approach to the case of Rift Valley Fever in Senegal

Yves M. Tourre[1,2]*, Jean-Pierre Lacaux[3], Cécile Vignolles[4] and Murielle Lafaye[4]

[1]METEO-France, Direction de la Climatologie, Toulouse, France; [2]Lamont-Doherty Earth Observatory (LDEO) of Columbia University, Palisades, NY, USA; [3]Observatoire Midi Pyrénées (OMP), Université Paul Sabatier (UPS), Toulouse, France; [4]Centre National d'Etudes Spatiales (CNES), Toulouse, France

Background: Climate and environment vary across many spatio-temporal scales, including the concept of climate change, which impact on ecosystems, vector-borne diseases and public health worldwide.
Objectives: To develop a conceptual approach by mapping climatic and environmental conditions from space and studying their linkages with Rift Valley Fever (RVF) epidemics in Senegal.
Design: Ponds in which mosquitoes could thrive were identified from remote sensing using high-resolution SPOT-5 satellite images. Additional data on pond dynamics and rainfall events (obtained from the Tropical Rainfall Measuring Mission) were combined with hydrological in-situ data. Localisation of vulnerable hosts such as penned cattle (from QuickBird satellite) were also used.
Results: Dynamic spatio-temporal distribution of *Aedes vexans* density (one of the main RVF vectors) is based on the total rainfall amount and ponds' dynamics. While Zones Potentially Occupied by Mosquitoes are mapped, detailed risk areas, i.e. zones where hazards and vulnerability occur, are expressed in percentages of areas where cattle are potentially exposed to mosquitoes' bites.
Conclusions: This new conceptual approach, using precise remote-sensing techniques, simply relies upon rainfall distribution also evaluated from space. It is meant to contribute to the implementation of operational early warning systems for RVF based on both natural and anthropogenic climatic and environmental changes. In a climate change context, this approach could also be applied to other vector-borne diseases and places worldwide.

Keywords: *climate change*; *public health*; *remote sensing*; *risk mapping*; *vector-borne diseases*; *Rift Valley Fever*; *early warning systems*; *Health Information System*

Received: 19 July 2009; Revised: 21 August 2009; Accepted: 21 August 2009; Published: 11 November 2009

Rationale

Variation and change in climate

The climate changes and varies on many spatio-temporal scales. Natural variability in climate is a function of: (i) the relative position of the sun (and its activity such as sunspots, radiation, magnetism, eruption) and the earth; (ii) the Milankovitch cycles (1); and (iii) the interactions between the components of the climate system, i.e. the atmosphere, the hydrosphere, the cryosphere, the biosphere and the lithosphere. For centuries a panoply of climate signals have been noted, ranging from the diurnal, to multi-decadal effects including seasonal, quasi-biennial (QB), El-Niño/Southern Oscillation (ENSO), quasi-decadal (QD) and inter-decadal (ID) oscillations (2). Adding to these natural cycles and oscillations is the anthropogenic component from population increase, energy needs and associated pollution. Natural climate oscillations interact with the anthropogenic climate change component, and directly impact ecosystems, public health and socio-economic conditions. The natural variability of the global climate during the 20th century is reproduced in Fig. 1 [see also (3)].

Climate change and public health

Climate change *alters* regional and local social and economic dynamics with the potential of bringing additional inequalities all around the world (4). This could

Citation: Global Health Action 2009. DOI: 10.3402/gha.v2i0.2053

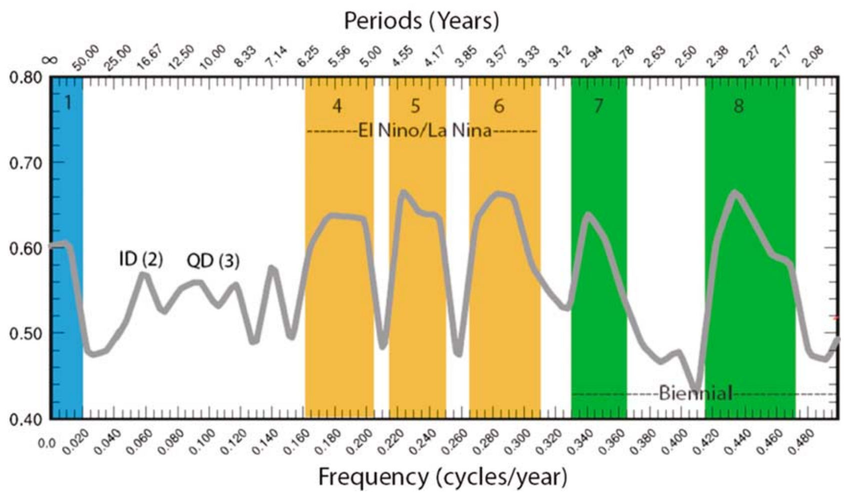

Fig. 1. During the 20th century a global statistical analysis in the frequency-domain of both sea-surface temperature and sea-level pressure, allows identification of natural climate signals. Coloured bands highlight those signals with their percentage of variance displayed on the ordinates, i.e. secular signal or penta-decadal (blue band, signal # 1), El-Niño/Southern Oscillation or ENSO (orange bands, signals # 4, 5 and 6), the quasi-biennial signal (green bands, signals # 7 and 8). Signal # 2 ID or inter-decadal, and signal # 3 QD or quasi-decadal, are more locals and found over the Pacific and Atlantic Oceans, respectively (2). The anthropogenic climate change is interacting and modulates the above climate signals.

result in economic migration, and reduced access to primary resources. Climate change had impacts in historical times with respect to the development of many cultures. Changes have been observed in nutrient budgets and nutrient cycles, with enhanced human pressure through population increase and public health impacts. The total primary energy demand is expected to increase by ~60% during the first quarter of the 21st century. Most of this energy will come from fossil sources, and unfortunately only 1–2% is expected from renewable sources. Such disequilibrium is likely to create socio-economic chaos, regional and local vulnerability in terms of prices and supply, and have considerable impacts on the environment and public health, for example, on infectious diseases, respiratory and circulatory problems, pollution, allergen-related diseases and impaired immune systems. Public health issues will also be exacerbated by poor water quality and malnutrition, leading to huge costs and increasing poverty.

Climate change *perturbs* important physical and biological systems to which human populations are generally biologically and culturally adjusted. The various environmental changes linked to natural and anthropogenic variability and changes in climate, and loss of biodiversity though land-use changes, will all have their own impacts on public health. It is recognised that beneficial impacts such as decreases in cold-related deaths are also anticipated. Direct influence from demographic factors may increase risks of infectious diseases being transmitted from person-to-person. Thus, socio-economic impacts on infectious diseases and public health, arising from climate and environmental changes, require attention. Most emerging (or re-emerging) infectious diseases (including vector-borne diseases) are due partly to changes in 'microbial traffic', for example, the introduction of pathogens from wildlife into human populations already at risk. Changes in transmission of diseases by vectors (such as mosquitoes) may arise from new vector reservoirs in different habitats, the changing climate and environmental determinants of which deserve further investigation. These processes may depend upon ecological and environmental factors, but the spread of diseases is also facilitated by climate variability/change, population migration, demographic crowding effects, sanitation levels and/or breakdowns in public health systems. As of today, the increase in occurrence of many infectious diseases reflects the compounded effects of climatic and environmental changes, population increases, economic, social and technological changes.

Climate change and infectious diseases

The challenge for assessing socio-economic impact of infectious diseases (~75% of actual infectious diseases in humans are zoonoses) cannot be addressed without considering both abiotic and biotic environmental factors that affect the maintenance and transmission of the diseases. The last 25 years have witnessed an explosion of environmentally related diseases and disorders, with strong environmental forcing and adaptation or lack thereof. For infectious diseases, this includes increases in prevalence, incidence and geographical distribution across wide taxonomic ranges, related to climatic and environmental changes and practical changes in land-use. The understanding of these associated changes represents an important step for moving away from the more traditional individual-centred view of microbiology and medical epidemiology.

Direct health effects of climate variability and change include: (i) changes in mortality and morbidity arising from heat-waves and thermal stress (such as in 2003 over southwest Europe; and to a lesser degree in 2007 over Italy and Greece); (ii) respiratory ailments associated with modified concentrations of particulate matter and aero-allergens (e.g. spores, moulds) and/or air pollutants; and (iii) health consequences from extreme weather events, including storms, floods and gales.

Indirect health effects arise from perturbation of more complex ecological systems, and include changes in the ecology, range and activity of vectors and associated diseases (i.e. malaria, West Nile virus, Rift Valley Fever (RVF), avian flu, chickungunya, dengue fever and others) (5); changes in the environment for water-borne diseases and pathogens (i.e. gastro-intestinal infections, vibrio diseases including cholera, diseases from polluted water and others); changes in the atmospheric boundary layer, and transmission of air-borne diseases (i.e. meningitis, respiratory ailments and others); changes in regional and local agricultural practices and food availability which can lead to malnutrition and lack of fresh water. Public health can also be affected by massive population movements along narrow coastal regions, and by regional conflicts arising from declining agricultural and water resources. Some diseases have already extended their endemic range, such as leishmaniasis in southern Europe and the Maghreb. Climate change may facilitate habitat extension for sandfly and other phlebotome vectors northwards, whilst the ecology and geography of the tick species responsible for transmitting Lyme disease may profoundly change.

Climate change and decision-making

Climate change affects regional socio-economic costs and losses, through changes in temperature and soil moisture, inherent use of fertilisers and pest and pathogen activity. Decision-making models to be used must include:

(1) Identification of 'normal' impacts of disease (in lives and economic terms).
(2) Definition of 'climate events' linked to 'health events' (epidemics, endemics, pandemics).
(3) Definition of 'increased impacts' and socio-economic losses.
(4) Identification of methods for loss mitigation.
(5) Definition of real costs for effective implementation of services such as Health Information Systems (HIS).
(6) Quantification of real savings (including lives) if a well-identified 'health event' does not occur.

Even if regional modelling studies consistently indicate that tropical and sub-tropical countries would be most affected, changing climate and environment at higher latitudes must also be considered. Forecasting climate change impacts on public health requires the development of scenario-based risk assessments which must include generalised assessment of the consequences from complex demographic, social and economical disruptions. Integrated mathematical modelling must be used if one wants to estimate the future impacts of climate change on health (6). Such new modelling requires that each component of the chain of causation: climate, environmental and social change is fully represented.

Uncertainties do remain and are due to future industrial and economic activities, interactions between and within natural systems, and differences in sensitivity of disease systems and vulnerability of populations. Differences in population vulnerability could arise from heterogeneity of human culture, social relations and behaviour. Non-linear uncertainties arise from the stochastic nature of the biophysical systems being modelled. Local anthropogenic deforestation may directly alter the distribution of vector-borne diseases while also cause a local increase in temperature (positive feedback).

Climate and environmental changes and remote sensing

Public health indicators and disease surveillance activities should be integrated with other in-situ monitoring systems developed by the United Nations, such as Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), Global Terrestrial Observing System (GTOS) and the integrated Global Earth Observation System of Systems (GEOSS). Today, the use of satellites allows monitoring in high resolution of changes in environmental and climatic parameters. This provides an important continuum of observational spatio-temporal scales on both oceanic and terrestrial environmental structures, which should never be interrupted.

Tele-epidemiology

Infectious diseases remain a considerable challenge to public health. In the context of climate change and the rapidly increasing population as mentioned above, some epidemics are emerging or re-emerging such as the RVF over West Africa, dengue fever over northern Argentina and chikungunya in the Indian Ocean and northern Italy, among others.

The conceptual approach

Following the French contribution and presentation during the Johannesburg Summit 2002, a new conceptual approach has been developed: so-called tele-epidemiology

(7). It aims to monitor and study the spread of human and animal infectious diseases which are closely tied to climate and environmental changes. By combining satellite-originated data on vegetation (SPOT), meteorology (Meteosat, TRMM), oceanography (Topex/Poseidon; ENVISAT, JASON) with hydrology data (distribution of lakes, water levels in rivers, ponds and reservoirs), with clinical data from humans and animals (clinical cases and serum use), predictive mathematical models can be constructed.

Lately as a part of the French Ministry of Research's Earth–Space Network, a pilot sentinel network has been deployed in Niger and Burkina Faso for monitoring infectious diseases such as malaria, which is also tied to changing environmental factors. This integrated and multidisciplinary approach of tele-epidemiology includes:

(1) monitoring and assembling multidisciplinary in-situ datasets to extract and identify physical and biological mechanisms at stake;
(2) remote-sensing monitoring of climate and environment, linking epidemics with 'confounding factors' such as rainfall, vegetation, hydrology and population dynamics; and
(3) use of bio-mathematical models for epidemic dynamics, vector aggressiveness and associated risks.

As such an interactive tool contributing to HIS on re-emergent and new infectious diseases (RedGems) was born (8). It constitutes the main pillar of tele-epidemiology by facilitating real-time monitoring of human and animal health and the exchanges of epidemiological, clinical and entomological data. The primary mission of RedGems (www.redgems.org) is to contribute towards the development of early warning systems (EWS) for infectious diseases and contribute to the main three actions of tele-epidemiology presented above. The overall objective is to attempt predicting and mitigating public health impacts from epidemics, endemics and pandemics.

The Rift Valley Fever (RVF) case

The various components of the new conceptual approach described above have been thoroughly tested with regard to the emerging RVF in the Ferlo (Senegal). This successful approach has led the Senegalese government to provide funding, and extend the approach to all risk zones (i.e. hazards + vulnerability) where populations and cattle are exposed (9).

The Ferlo region in Senegal, became prone to RVF in the late 1980s with the appearance of infected vector mosquitoes of the *Aedes vexans* and *Culex poicilipes* species (10, 11). The latter proliferate near temporary ponds and neighbouring humid vegetation. RVF

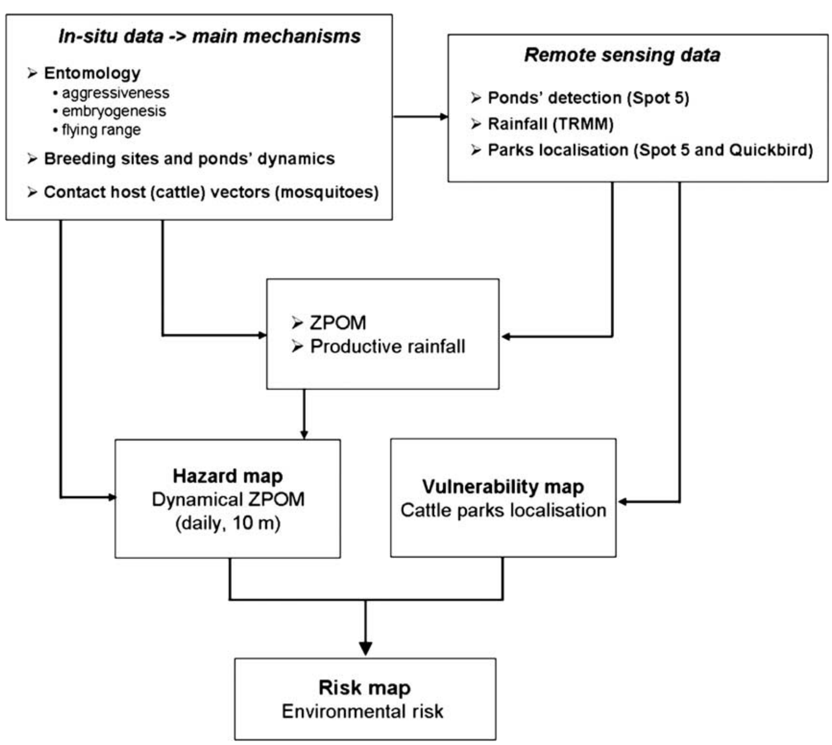

Fig. 2. Integrated conceptual approach. The basic components for the concept are presented in the top three boxes: in-situ data (upper left), remotely sensed data (upper right) and Zone Potentially Occupied by Mosquitoes or ZPOMs and 'productive rainfall' in terms of production of mosquitoes/vectors (centre). The bottom three boxes distinguish between hazards (bottom left), vulnerability (bottom right), both leading to the environmental risks (very bottom).

epizootic outbreaks in livestock cause spontaneous abortions and perinatal mortality. So far, human-related disease symptoms are often limited to flu-like syndromes but can include more severe forms of encephalitis and haemorrhagic fevers. As a result, local socio-economic resources can be seriously affected. The ultimate goal was to use specific Geographical Information System (GIS) tools (12) and remote-sensing (RS) images and data to detect potential breeding ponds and evaluate RVF transmission and areas potentially at risk, characterised as Zones Potentially Occupied by Mosquitoes (ZPOMs).

A schematic design of the integrated conceptual approach to determine the environmental risk levels of RVF is presented in Fig. 2. The upper left box in the figure identifies key entomological factors for *A. vexans* (flying-range, aggressiveness and embryogenesis), environmental factors (rainfall distribution, limnimetry and pond dynamics) as well as pastoral data such as the zones where animals are penned at night. From the upper right box, the detection of lead environmental and climatic factors (mainly rainfall) favouring the mechanisms presented are highlighted. For example, localities and optimal pond conditions for the breeding and hatching of *A. vexans* can be modelled (13). The central box refers to the ZPOMs derived from pond dynamics after a 'productive rainfall' event, and which includes the flying ranges of *A. vexans*. The integration of all the above components leads to the notion of risks: hazards and exposure vulnerability of hosts. This original approach (14) bridges the physical and biological mechanisms, linking environmental conditions to the 'production' of RVF vectors and accompanying potential risks.

Possible hazards in the vicinity of fenced-in hosts are displayed in Fig. 3, where the Barkedji area is shown with the mapped ZPOMs. Thus, parks and villages can easily be identified. Out of 18 rainfall events obtained from TRMM for the 2003 rainy season, seven were considered as 'productive' with regard to *A. vexans* production (based on entomological studies).

Conclusion

Climate variability and change, environmental risks and public health are all associated. In the case of potential RVF epidemics, mechanisms linking rainfall variability (and trends), density and aggressiveness of vectors and vulnerability of hosts are presented. Using observations from space, we constructed the dynamic evolution of ZPOMs [Fig. 4; see also animated on-line version in (9)

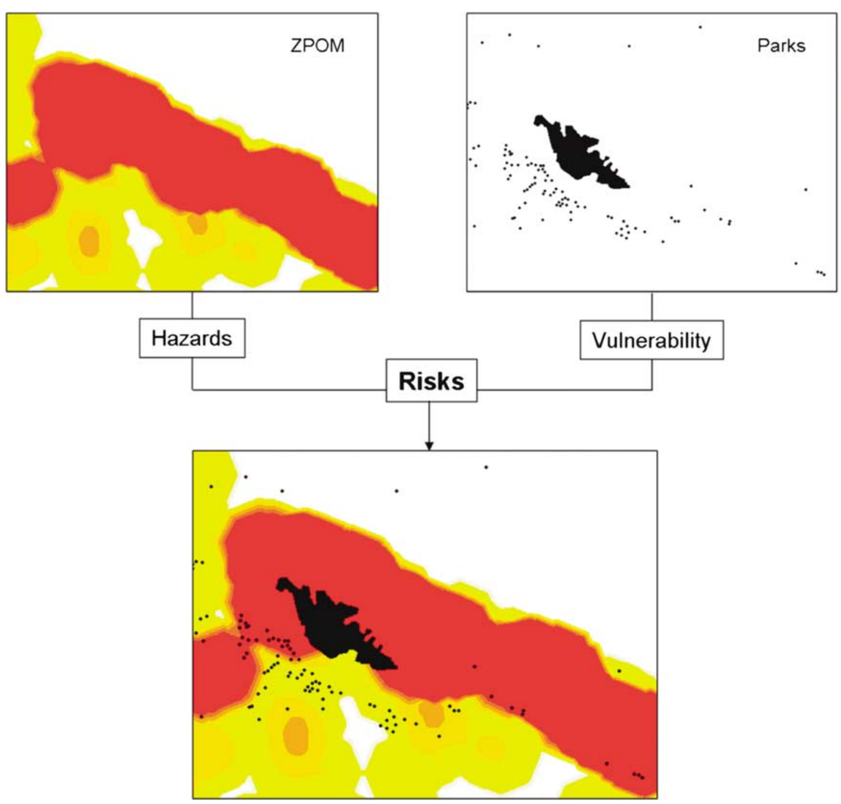

Fig. 3. Zone Potentially Occupied by Mosquitoes, or ZPOMs with ranked hazards from yellow (low hazards) to red (high hazards). ZPOMs in the Barkedji area constructed from the pond distribution after a single rainfall event (top left). Localisation of the Barkedji village and ruminants' fenced-in areas (vulnerability, from QuickBird) in black for the same area and period (top right). Potential risks i.e. hazards + vulnerability are shown by super-imposing the two pictures (bottom).

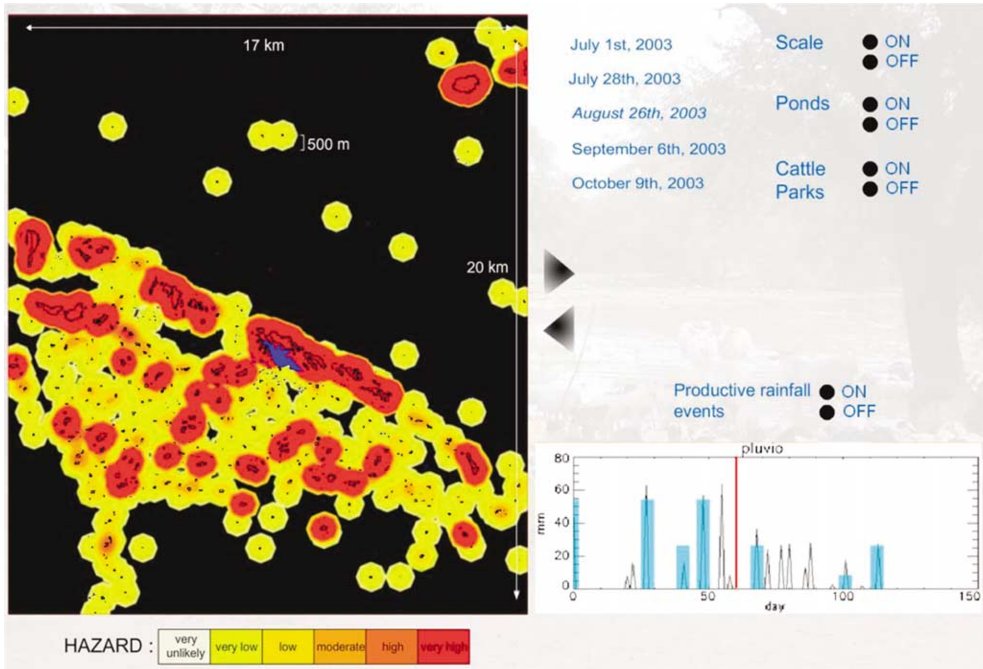

Fig. 4. Dynamic Zones Potentially Occupied by Mosquitoes (ZPOMs) and ranked hazards+risks. Dynamic ZPOMs with ranked hazards (from very unlikely and very low in yellow, to very high in red, bottom scale) and ponds distribution (in blue) during the 2003 rainy season. From the hyperlinked figure available on-line paper, by clicking on the two fat black arrows, animated ZPOMs from 'productive rainfall' (highlighted in blue, at the bottom right) are displayed (upper arrow for forward motion, lower arrow for backward motion) along with the relative parks' locations (vulnerability). The starting date is 28 June 2003. ZPOMs for specific date can also be displayed. The vertical red marker is for accurate time positioning on a daily basis.

available at www.geospatialhealth.unina.it] from the distribution and development of ponds was crucial. It allowed direct identification of RVF risks from discrete and 'productive rainfall' events such as local deep atmospheric convections and propagating squall-lines. This remote-sensing approach and the new integrated concept belongs to the so-called tele-epidemiology developed at CNES (14).

Climatic and environmental variability and changes identified from space provide the elements for the mapping of risk zones in which necessary conditions for the RVF virus to circulate and be transmitted exist. The evolution of the ZPOMs during the rainy season reveals areas in which populations and cattle of the Ferlo region in Senegal are exposed. There are many strengths in this approach. It can be used in quasi real-time, and results can be linked with biological modelling for virus transmission and circulation and more classical epidemiological models. Socio-economic risks may be reduced and mitigated, based upon statistical evaluation of the seasonal rainfall forecasts which can be assessed a few months prior to the rainy season and subsequently updated. For example, results can be immediately applied upstream by the Senegalese Direction de l'Elevage (DIREL) though strategic displacement of fenced-in areas for cattle penned at night, during the course of the rainy season. Nonetheless, socio-economic problems may still arise if the relevant information has not been distributed operationally to all parties involved, through regional HIS. Ultimately, the fully integrated approach should help in understanding the mechanisms leading to potential RVF epidemics and improve the RVF EWS.

The conceptual approach presented might not apply directly for other vector-borne diseases, whose vectors have different behaviours. Thus, physical and biological mechanisms for other infectious diseases and places (including higher latitude regions) need to be studied individually. A similar methodology using space observations may be used, particularly in places where climate and environment are foreseen to change rapidly, as for example currently being implemented for malaria in Burkina Faso.

Acknowledgements

The authors would like to thank Dr. Antonio Güell, Head of the Application and Valorisation department at CNES, for his unconditional support. Tourre would like to thank Drs. Philippe Dandin and Mike Purdy, Directors of the Climatology Department at METEO – France and of the LDEO of Columbia University, respectively, for facilitating this applied research. This is an LDEO contribution #7296.

Conflict of interest and funding

The authors have not received any funding or benefits from industry to conduct this study.

References

1. Milankovitch M. 1930: Mathematische Klimalehre und Astronomische Theorie der Klimaschwankungen, Handbuch der Klimalogie Band 1. Teil A Borntrager: Berlin; 1930.
2. Tourre YM, White WB. Global climate signals and equatorial SST variability in the Indian, Pacific and Atlantic oceans during the 20th century. Geophys Res Lett 2006; 33: L06716.
3. Lacaux J-P, Tourre YM. Impacts des changements climatiques. Le climat et sa variabilité ont-ils un impact sur la santé humaine? Biofutur 2006; 270: 22–4.
4. Plan Bleu. Climate change and energy in the Mediterranean. Part 1, Chapter 1: Mediterranean Basin: climate change and impacts during the 21st century. Report 2008. Sophia Antipolis, France: Le Plan Bleu; 2008, pp. 52–4.
5. Takken W, Martens P, Bogers RJ. Environmental change and malaria risk: global and local implications. New York, LLC: Springer-Verlag; 2006, p. 139.
6. Martens P. Climate change 2001: vulnerability and sustainability. IPCC TAR report. Available from: www.grida.no/climate/ipcc_tar/wg2/539.htm [cited September 2009].
7. Lafaye M. Nouvelles applications spatiales pour la santé: la télé-épidémiologie pour le suivi des fièvres aviaires. Toulouse cedex, France: CNES Magazine; 2006, 30–31 February 2006.
8. Marechal F, Ribeiro N, Lafaye M, Güell A. Satellite imaging and vector-borne diseases: the approach of the French National Space Agency (CNES). Geospat Health 2008; 3: 1–5.
9. Vignolles C, Lacaux J-P, Tourre YM, Bigeard G, Ndione J-A, Lafaye M. Rift Valley Fever in a zone potentially occupied by *Aedes vexans* in Senegal: dynamics and risk mapping. Geospat Health 2009; 3: 211–20.
10. Lacaux J-P, Tourre YM, Vignolles C, Ndione J-A, Lafaye M. Classification of ponds from high spatial resolution remote sensing: application to Rift Valley Fever epidemics in Senegal. J Remote Sensing Env 2007; 106: 66–74.
11. Tourre YM, Lacaux J-P, Vignolles C, Ndione J-A, Lafaye M. Mapping of zones potentially occupied by *Aedes vexans* and *Culex poicilipes* mosquitoes, the main vectors of Rift Valley Fever in Senegal. Geospat Health 2008; 3: 69–79.
12. Tourre YM, Fontannaz D, Vignolles C, Ndione J-A, Lacaux J-P, Lafaye M. GIS and high-resolution remote sensing improve early warning planning for mosquito-borne epidemics. Healthy GIS, GIS for Health and Human Services, ESRI; 2007: 1–4.
13. Bicout DF, Porphyre T, Ndione J-A, Sabatier P. Modeling abundance of *Aedes* and *Culex* spp. in rain-fed ponds in Barkedji, Senegal. Proceedings of the 10th International Symposium on Veterinarian Epidemiology and Economics, Vina del Mar, Chile, 17–21 November 2003, p. 84.
14. CNES, 2008: Method for tele-epidemiology (Méthode pour la télé-épidémiologie). Patent pending # PCT/FR2009/050735.

***Yves M. Tourre**
Météo-France
Direction de la Climatologie
42 Avenue Gaspard Coriolis
FR-31057 Toulouse, France
Tel: +33 5 61 07 81 49
Email: yvestourre@aol.com